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S-BAND SHALLOW BULK ACOUSTIC WAVE (SBAW) MICROWAVE SOURCE

FINAL REPORT

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TRW
DEFENSE AND SPACE SYSTEMS GROUP

CONTENTS

1. INTRODUCTION AND SUMMARY

This report describes the results of the Phase I investigation of the S-Band Shallow Bulk Acoustic Wave (SBAW) microwave source program. The SBAW microwave sources were designed, fabricated and evaluated under NASA Contract NAS5-26002. The primary purpose of this effort was to establish techniques necessary to fabricate a high performance S-Band microwave signal source using state-of-the-art SBAW oscillator technology. For Phase I, the objectives were:

- Develop 1.072 GHz SBAW delay lines.
- Fabricate five hybrid 1.072 GHz SBAW reference oscillators.
- Investigate SBAW in aluminum nitride on sapphire $A\ell N/A\ell_2O_3$.
- Perform design study of the 2.144 GHz SBAW delay line.
- Investigate SBAW delay line oscillator frequency selectability/settability.

The key element in the SBAW microwave source is the SBAW delay line. For Phase I, the 1.072 GHz SBAW delay line was developed. Section 2 of this report describes in detail the theory of operation, the design, fabrication and test of the 1.072 GHz delay line. This section also describes a cost-effective technique for mounting and packaging SBAW devices to achieve low aging rates.

The 1.072 GHz SBAW oscillators fabricated for this program are described in Section 3. The existing hybrid design developed under a separate NASA program, "15 GHz Modulator/Exciter", Contract No. NAS5-25354 , was used to construct these oscillators. The stability of four of the five oscillators was extensively evaluated. This included measurements on phase noise, frequency dependence on temperature, and aging characteristics. The remaining oscillator was fabricated with plastic covers so that one could observe both the SBAW delay line and the amplifier circuit.

Sections 3, 4 and 5 describe the investigation of SBAW in $A\ell N/A\ell_2O_3$, the design of the 2.144 GHz SBAW delay line, and the study of frequency selectability and settability of SBAW oscillators. The bulk wave structures of the $A\ell N/A\ell_2O_3$ were investigated for both the R plane and basal plane of sapphire. No useful SBAWs were discovered. Various design options for 2.144 GHz SBAW delay lines were explored. From this investigation, two baseline designs were found. The method of selecting and setting oscillator output frequency by selecting substrate orientation angle was also established.

2. 1.072 GHz SBAW DELAY LINE DEVELOPMENT

Shallow Bulk Acoustic Wave (SBAW) devices are of great interest as frequency sources because of their superior properties when compared to Surface Acoustic Wave (SAW) devices. SBAWs have demonstrated higher frequency capability, better temperature stability, and lower propagation loss than SAWs. In addition, SBAW oscillators are projected to have better aging characteristics than their SAW counterparts.[1-3]

The NASA system requirement was to have a stable source at 2.144 GHz. However, since SBAW delay lines at 2 GHz require submicron linewidths which make them costly to fabricate, a detailed investigation was first performed at 1.072 GHz. The 1.072 GHz SBAW delay line development provided the design and fabrication techniques necessary for the development of the 2.144 GHz device. It also provides a vehicle for a comparison between two approaches: direct generation at 2 GHz or generation at 1 GHz followed by 2X multiplication.

This section starts with a brief discussion of the SBAW properties in rotated Y-cut quartz and how they affect the material selection and device design. The trade-off between various design considerations are then described. The fabrication, mounting and packaging of the SBAW delay lines are also addressed.

2.1 SBAW IN ROTATED Y-CUT QUARTZ

Shallow Bulk Acoustic Waves (SBAWs) are essentially bulk waves which propagate just below the crystal surface. They can be launched and detected with interdigital transducers. SBAWs have been observed in quartz, lithium niobate, lithium tantalate and berlinite. Of these materials, only quartz and berlinite have cuts with a zero first-order temperature coefficient near room temperature. The crystal quality of berlinite is presently not suitable for device application. Thus, quartz was selected for this program.

The SBAW in quartz has been extensively searched and characterized.[3] SBAWs are found to propagate in singly rotated Y-cut quartz with propagation direction at 90° off the X-axis. These SBAWs are pure shear plane waves with polarization parallel to the surface and perpendicular to the direction of propagation. The coordinate axis of SBAW devices in these substrates is shown in Figure 2-1. The wave velocity, coupling coefficient,

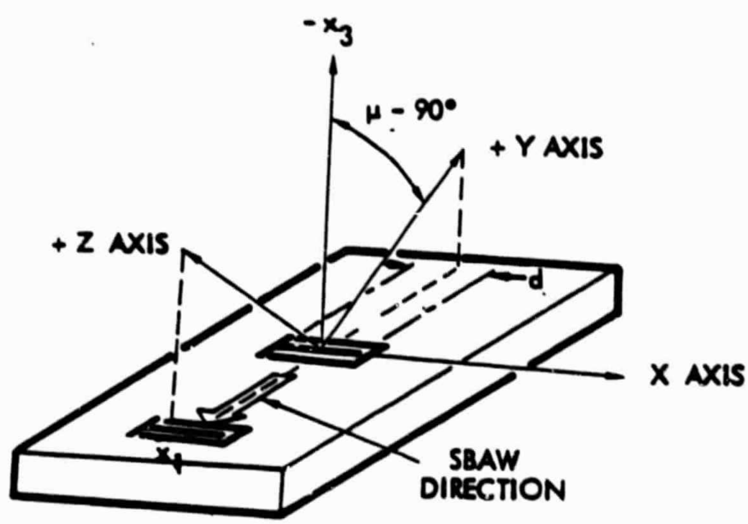


Figure 2-1. Geometry of a SBAW Device on Rotated Y-Cut Quartz

and temperature coefficient of the SBAW as a function of substrate angle θ has been theoretically calculated and is summarized in Figures 2-2, 2-3, and 2-4. The horizontal axis of these figures is expressed in μ, which is the Euler angle notation. To translate into θ, one simply subtracts 90° from μ.

For oscillator applications, the SBAWs are required to be temperature stable. As shown in Figure 2-4, there are two regions of θ where the first order temperature coefficient of delay vanishes at room temperature. Specifically, the θ's for temperature stable cuts are +35.5° and -50.5°. In actual devices, the metal loading effect caused by the metallic fingers shifts the temperature stable cut angles of θ by a few degrees. The exact magnitude depends on the thickness of the metallization. These effects have been quantitatively evaluated and are incorporated into the selection of the substrate orientation.

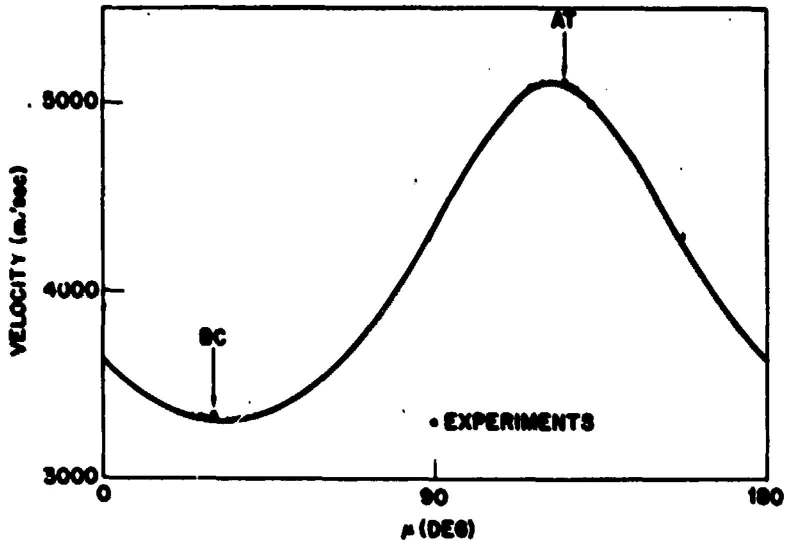


Figure 2-2. Velocity of SBAW in Rotated Y-Cut Quartz

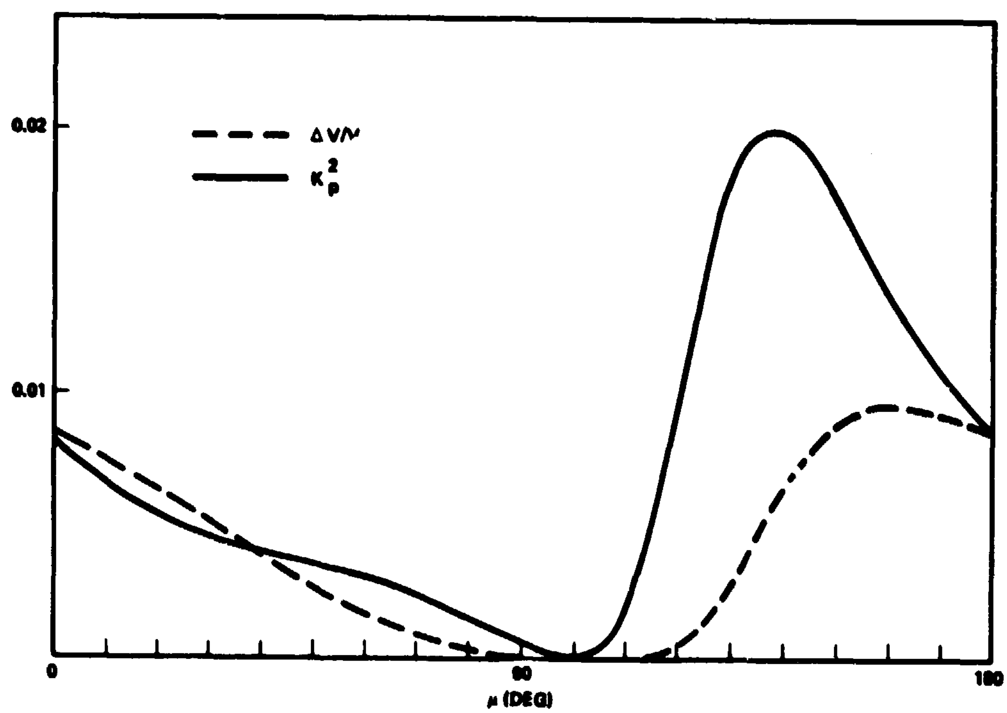


Figure 2-3. Δv/v and K_p^2 of SBAW in Rotated Y-Cut Quartz

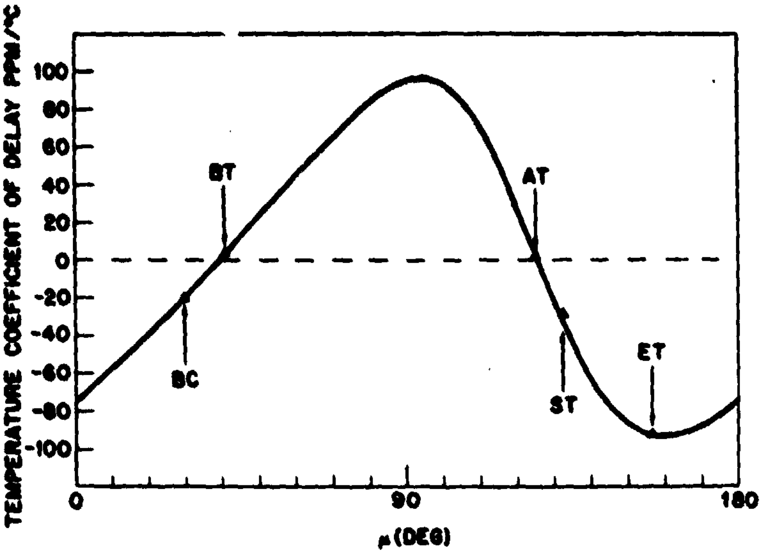


Figure 2-4. First-Order Temperature Coefficient of Delay of SBAW in Rotated Y-Cut Quartz

The comparison between the wave properties of the two temperature stable orientations is summarized in Table 2-1.

Table 2-1. Comparison of SBAW Properties Between +35.5° and -50.5° Rotated Y-Cut Quartz

	+35.5°	-50.5°
Wave Velocity	5100 m/sec	3331 m/sec
Coupling Coefficient	1.44×10^{-2}	0.41×10^{-3}
Mass Loading Effect ($\Delta v/v$ for $t/\lambda = 0.01$)	0.16%	0.1%
Wave Attenuation	0.83 dB/μsec	2.0 dB/μsec
Temperature Stability (-55°C to +85°C)	±125 ppm	±55 ppm

From this comparison, it is obvious that +35.5° has the advantage of high wave velocity, high coupling coefficient, and low wave attenuation. Its sensitivity to metal loading can also be an advantage since it provides a means for frequency trimming. The -50.5°, on the other hand, has the advantage of better temperature stability. The overall property of the +35.5° cut made it a more attractive substrate. For the Phase I investigation, substrates with rotation angle near +35.5° were extensively employed.

2.2 DELAY LINE DESIGN

The key element in the SBAW oscillator is the SBAW delay line. The SBAW delay line has two important aspects in an oscillator circuit: time delay and frequency selectivity. For a single mode oscillator, the passband of the delay line must be narrower than 1/t which is equal to the mode spacing of the oscillator. The basic structure of a SBAW delay line is similar to a SAW delay line. As shown in Figure 2-5, interdigital transducers are used to launch and detect the SBAW. The particle motion is in the plane of the crystal surface and perpendicular to the propagation direction. The design principles and the result of design trade-off study are discussed in this Section.

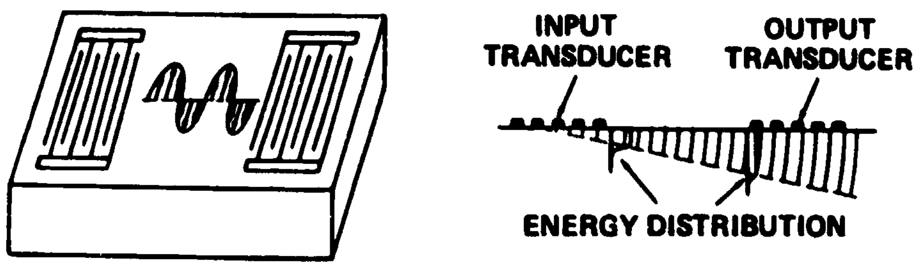
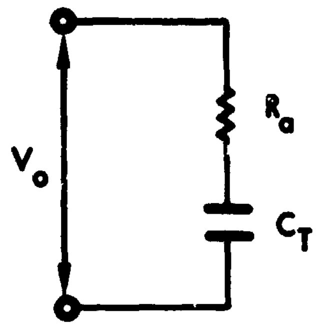


Figure 2-5. Basic SBAW Device Configuration

2.2.1 Design Principles

The conventional SBAW interdigital transducer has uniform width and periodic spacing. Its impedance and insertion loss can be calculated by using the equivalent circuit model developed at TRW. The frequency response can be simulated by using a delta functional model. The resultant transfer function of response of the SBAW delay line is just the product of the two individual transfer functions making up the delay line.

The equivalent circuit of SBAW transducers is represented by radiation resistance in series with the capacitance C_T as shown in Figure 2-6.



$$R_a \approx \frac{2}{\pi} \frac{1}{\sqrt{N}} K_p^2 \frac{1}{\omega_c C_s}$$

$$C_T = N\, C_s$$

Figure 2-6. Equivalent Circuit Model for a SBAW Transducer on Quartz and Berlinite

The capacitive reactance is given by

$$X_c(\omega_c) = \frac{1}{j\omega_c N C_s}$$

The impedance of the transducer $X(\omega_c)$ is thus given by

$$Z(\omega_c) = R_a(\omega_c) + \frac{1}{j\omega_c C_T}$$

R_a in this SBAW model is quite similar to that used in the "in-line" model for SAW devices. The major difference is the fact that the effective coupling of the SBAW is inversely proportional to N while it is independent of N for the SAW case.

The insertion loss of the SBAW is the sum of four contributions: conversion loss of the input transducer, conversion loss of the output transducer, propagation loss, and acoustic spreading loss. Following the technique developed for SAW, one can model the conversion loss of a transducer.

$$CL = 10 \log \frac{2\, R_a R_L}{(R_a + R_L)^2 + \left(\frac{1}{\omega_c C_T}\right)^2}$$

The factor of 2 in the numerator means that 3 dB bidirectional loss per transducer has been taken into account in this expression.

The propagation loss (PL) is proportional to the square of the operating frequency. At 1.0 GHz, the loss is 0.85 dB/μsec in 35° Y-rotated quartz.

The acoustic power spreading loss is due to the fact that not all the acoustic energy radiated toward the output transducer is received. The magnitude of the spreading loss is equal to the acoustic loss minus 6 dB. This 6 dB has been included in the transducer conversion loss discussed in the preceding page. The expression for the spreading loss is thus given by

$$SL = 10 \log \left(\frac{\lambda_c N}{4.5r}\right) - 6.$$

The total insertion loss of the SBAW delay line is thus given by the expression

$$IL = CL_1 + CL_2 + SL + PL$$

2.2.2 Design Trade-Off

The types of transducers fabricated in Phase I of this program are basically a modification of the conventional uniform transducer. Various configurations have been used to implement the delay line. Each of the transducer configurations is chosen to represent one design technique so that comparison can be made among the different techniques.

2.2.2.1 Fundamental Thinned Electrode Design

For transducers operating at the fundamental frequency, the transducer pattern is illustrated in Figure 2-7.

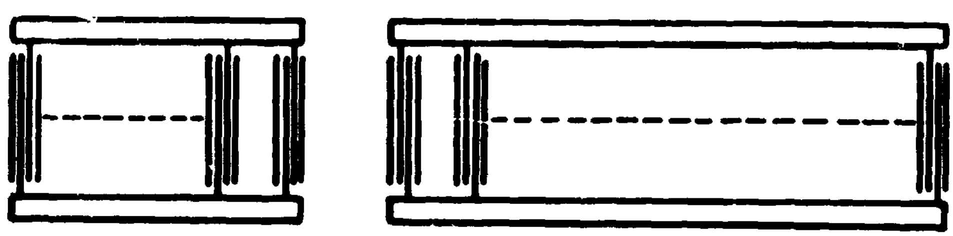


Figure 2-7. Thinned Electrode Transducer Configuration of SAW Delay Line Filter

A thinned electrode or open structure was used for both the input and output transducers. The thin electrode transducer is similar to the conventional interdigital transducer, except that there are periodic open areas between sets of electrodes. Instead of employing a double electrode configuration, dummy electrodes between the section were used to eliminate the dip in the passband caused by multiple reflections between sections. In addition, utilization of dummy electrodes instead of double electrodes reduces the linewidth resolution necessary, thus reducing the fabrication cost.

The design parameters of the delay line with fundamental thinned electrode design are summarized in Table 2-2.

Table 2-2. Design Parameters of Delay Line with Fundamental Electrode Transducers

	Transducer	
	Input	Output
Finger Width	1.19 μm	1.19 μm
No. of Sections	35	81
Section-to-Section Separation	$7\lambda_o$	$5\lambda_o$
Acoustic Aperture	$100\lambda_o$	$100\lambda_o$
Center-to-Center Separation Between Transducers	1904 μm	

A device was fabricated on 35.5° rotated Y-cut quartz. Figure 2-8 shows its frequency response. The measured results are summarized in Table 2-3 along with the designed values. Good agreement was obtained between the designed and measured values.

2.2.2.2 Third Harmonic Design

Harmonic operation offers a method by which SBAW delay lines can be made to operate at higher frequencies than otherwise possible. The configuration of the harmonic operating SBAW delay line is illustrated in Figure 2-9.

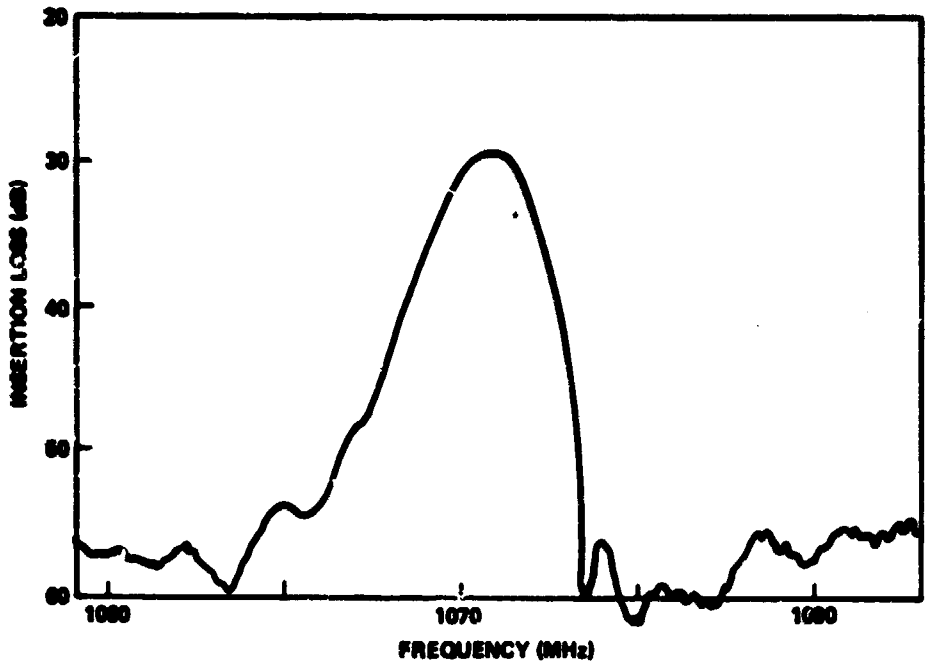


Figure 2-8. Frequency Response of SBAW Delay Line with Fundamental Thinned Electrode Transducers

Table 2-3. Comparison Between Designed and Measured Performances of the SBAW Delay Line with Fundamental Thinned Electrode Transducers

PARAMETERS	DESIGNED	MEASURED
CENTER FREQUENCY (MHz)	1071.67	1071.60
INSERTION LOSS (dB)		
UNMATCHED	≤35	29
MATCHED	<25	–
3 dB BANDWIDTH (MHz)	2.1	2.2
TIME DELAY (μSEC)/MODE SPACING (MHz)	0.378/2.65	0.340/2.94
OSCILLATOR Q ($\omega\tau/2$)	1272	1145

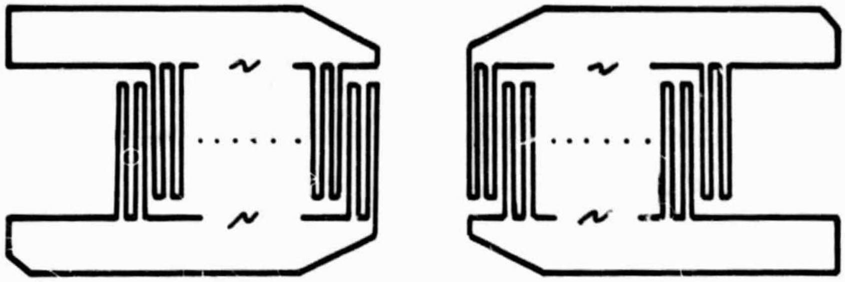


Figure 2-9. Third Harmonic Transducers

The harmonic operating transducer employs the split electrode configuration. For strong harmonic response, a configuration with two fingers up and two fingers down is employed. The transducer configuration of the delay line using third harmonic operation is summarized in Table 2-4. Identical input and output transducers were employed in this design.

Table 2-4. Design Parameters of the Delay Line with Two Identical Third Harmonic Transducers

Linewidth	1.78 μm
Number of Fingers (2 up, 2 down)	422
Transducer Length	316 λ_o
Acoustic Aperture	52 λ_o
Center-to-Center Separation Between Transducers	1904 μm

The frequency response of a SBAW delay line fabricated on 36.75° rotated Y-cut quartz using the third harmonic transducer design is shown in Figure 2-10. Its designed and measured performance is summarized in Table 2-5.

Table 2-5. Designed and Measured Performance of SBAW Delay Line with Third Harmonic Transducers

PARAMETERS	DESIGNED	MEASURED
CENTER FREQUENCY	1071.67	1072.0
INSERTION LOSS (dB)		
UNMATCHED	≤ 30	26
MATCHED	≤ 25	22
3 dB BANDWIDTH (MHz)	2.2	2.28
TIME DELAY (μSEC)/MODE SPACING (MHz)	0.374/2.67	0.362/2.76
OSCILLATOR Q (ωτ/2)	1260	1220
MINIMUM LINEWIDTH (μM)	1.78	1.78

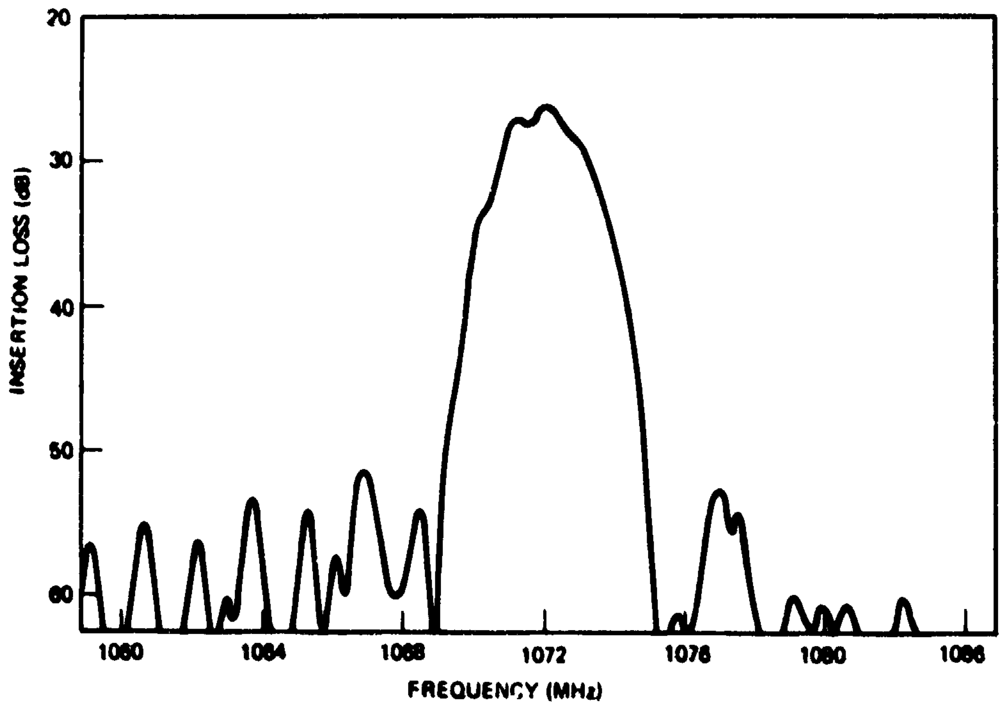


Figure 2-10. Frequency Response of SBAW Delay Line with Third Harmonic Transducers

2.2.2.3 <u>Delay Line with Energy Trapping</u>

Energy trapping provides a means to lower the propagation loss, thus increasing the delay time of SBAW devices. With energy trapping, the propagation loss due to the 1/r spreading of the SBAW energy is minimized. A high Q, low noise floor SBAW oscillator can therefore be constructed.

Several energy trapping techniques are available. These include dielectric layer, metal layer and gratings. These gratings can either be grooved gratings or metal strips. Experimentally, the most effective means of energy trapping is to use gratings. Metal grating was used in this investigation to trap the SBAW energy close to the surface.

A design which maximizes the amount of energy trapping was employed. Figure 2-11 shows the schematic of this configuration. It consists of two transducers with split fingers. The input transducer employed a thinned electrode design. Gratings with periods less than 1/4 of the wavelengths are placed everywhere in the acoustic wave path. The detailed design parameter is summarized in Table 2-6.

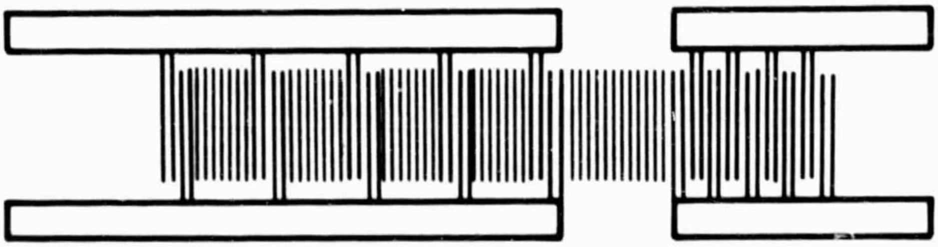


Figure 2-11. Schematic of Delay Line Employing Energy Trapping Gratings

The frequency response of the delay line using the energy trapping on 36.75° rotated Y-cut quartz is shown in Figure 2-12. The comparison between designed and measured parameters is summarized in Table 2-7.

Table 2-6. Design Parameters of the SBAW Delay Line with Energy Trapping Gratings

	Thinned Electrode Transducer	Uniform Transducer
Aperture	$90\lambda_o$*	$90\lambda_o$
Finger Width	1.78 μm	1.78 μm
Transducer Length	$730\lambda_o$	$202\lambda_o$
No. of Sections	25	-
Section-to-Section Separation	$30\lambda_o$	-
Section Length	$10\lambda_o$	-
Grating Linewidth	1 μm	-

*λ_o = wavelength at third harmonic

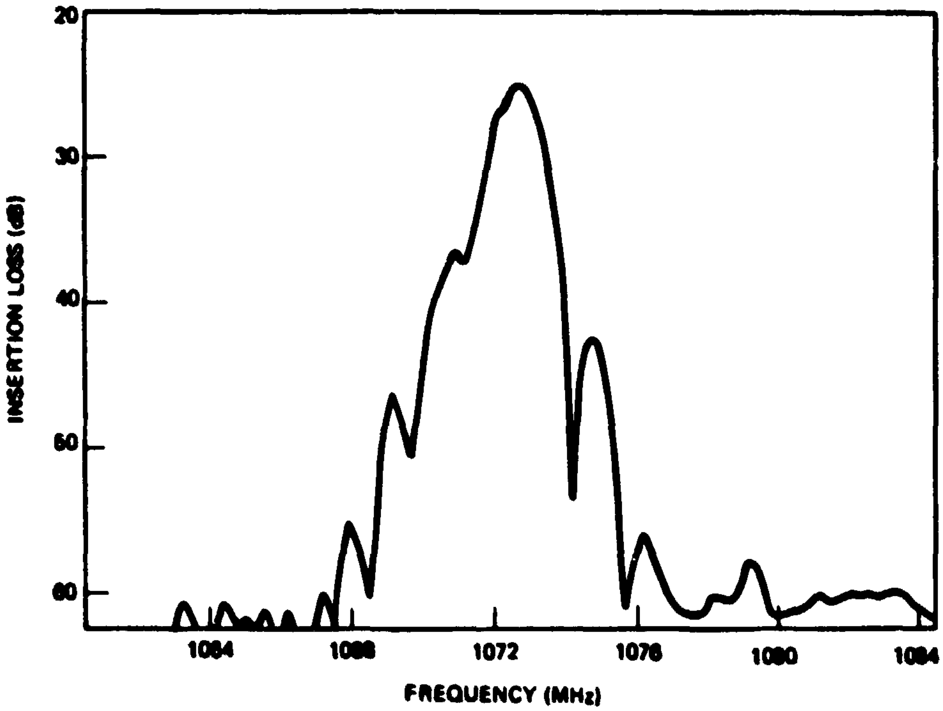


Figure 2-12. Frequency Response of SBAW Delay Line with Energy Trapping Gratings

Table 2-7. Comparison Between Designed and Measured Performance of Delay Line with Energy Trapping

PARAMETERS	DESIGNED	PRELIMINARY DATA
CENTER FREQUENCY (MHz)	1071.67	1072.77
INSERTION LOSS (dB)		
UNMATCHED	<35	25
MATCHED	<25	22.5
3 dB BANDWIDTH (MHz)	1.25	1.22
DELAY TIME (μSEC)/MODE SPACING (MHz)	0.680/1.47	0.625/1.6
OSCILLATOR Q ($\omega\tau/2$)	2288	2106
MINIMUM LINEWIDTH	1.0	1.0

2.2.2.4 Third Harmonic Segmented Transducer Design

The segmented transducer design as shown in Figure 2-13 was studied because it offered two potential advantages. It would allow the use of co-planar waveguide structure to couple signals in and out of the delay line with a minimum amount of electromagnetic feedthrough. It also promised to reduce the secondary metal loading effects because the acoustic wave generated at the far end of the long transducer travels under only half of the fingers, compared with equivalent in-line delay lines.

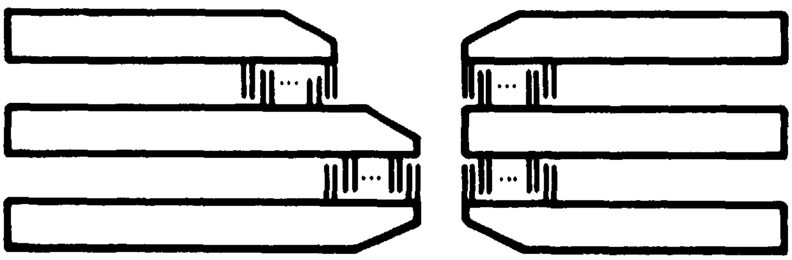


Figure 2-13. Segmented Transducer Design

The frequency response of the segmented delay line was poor. As shown in Table 2-8, the measured insertion loss is much higher than expected. This is due to phase mismatch between the two sections. Due to the 1/r spreading loss, the segmented transducer configuration was found not to be applicable to SBAW devices.

Table 2-8. Designed and Measured Parameters of the Device with Segmented Transducer Design

PARAMETERS	DESIGNED	MEASURED
CENTER FREQUENCY (MHz)	1071.67	1066.1
INSERTION LOSS (dB)		
UNMATCHED	$\leq$35	44
MATCHED	$\leq$25	–
3 dB BANDWIDTH (MHz)	2.1	1.9
TIME DELAY (μSEC)/MODE SPACING (MHz)	0.375/2.67	–
OSCILLATOR Q ($\omega\tau/2$)	1262	–
MINIMUM LINEWIDTH	1.78	1.78

2.2.2.5 Conclusion

The result of the design trade-off study is summarized in Table 2-9. The third harmonic design represents the optimum design choice since it has low insertion loss and better potential for higher frequency operation. The third harmonic design has been chosen as the baseline design for the 1.072 GHz SBAW delay line.

Table 2-9. 1.072 GHz SBAW Delay Line Design Tradeoffs

DESIGN ALTERNATIVES	RESULTS
Fundamental Thinned Electrode	Moderate Q, 29 dB unmatched insertion loss, 1.2 μm linewidth, extendable to 2 GHz
Third Harmonics	Moderate Q, 26 dB unmatched insertion loss, 1.78 μm linewidth, easily extendable to 2 GHz
Segmented Transducer	>40 dB insertion loss, poor response
Energy Trapping	High Q, 25 dB unmatched insertion loss, 1 μm linewidth, not easily extendable to 2 GHz

2.3 FABRICATION AND PACKAGING TECHNIQUES

Photolithographic processes developed at TRW were employed to fabricate the SBAW devices. The etching technique was used in the fabrication of the interdigital transducers. It is illustrated in Figure 2-14.

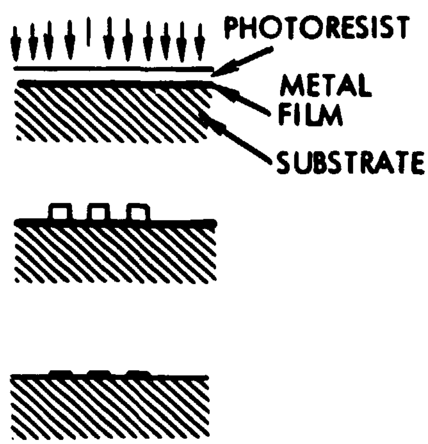


Figure 2-14. Schematic Illustration of Etching Techniques

In this process, a thin metal film is deposited on the quartz substrate followed by spin coating of Shipley 1350J positive photoresist. The surface is then exposed with a highly uniform monochromatic UV light source through a light field photomask. After exposure, the surface is developed, forming a transducer pattern over the metal film. The metallic pattern is defined by ion beam etching through the developed photoresist pattern. Ion beam etching was found to produce lines with better definition and reporducibility than the conventional chemical etching.

The SBAW delay line was packaged in a 20-pin Tekform flatpack. The procedures for device packaging is described below.

The SBAW delay line was mounted in the flatpack with 71-1 Ablestik adhesive. Only a small drop of Ablestik was applied to the back of the delay line so that most of the SBAW substrate is free from any stress that may arise from mounting. The Ablestik was cured in an oven with a continuous hydrogen flow for one hour at 300°C. Ablestik was selected because of its low outgassing rate, thereby increasing the possibility of having low aging rates.

SECTION 2 REFERENCES

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2. M. F. Lewis, "Surface Skimming Bulk Waves", Proc. IEEE Ultransonics Symp., p. 744, 1977.
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3. HYBRID 1.072 GHz SBAW REFERENCE OSCILLATOR

The use of Shallow Bulk Acoustic Wave (SBAW) delay lines as the frequency stabilizing element in oscillators is a relatively recent development. This section describes the operation, design, and performance of the 1.072 GHz SBAW oscillator constructed under Phase I of the program.

3.1 THEORY OF OPERATION

A SBAW oscillator consists of a SBAW delay line connected in a feedback loop with an amplifier as shown in Figure 3-1. This circuit will oscillate at any frequency for which the total phase shift around the

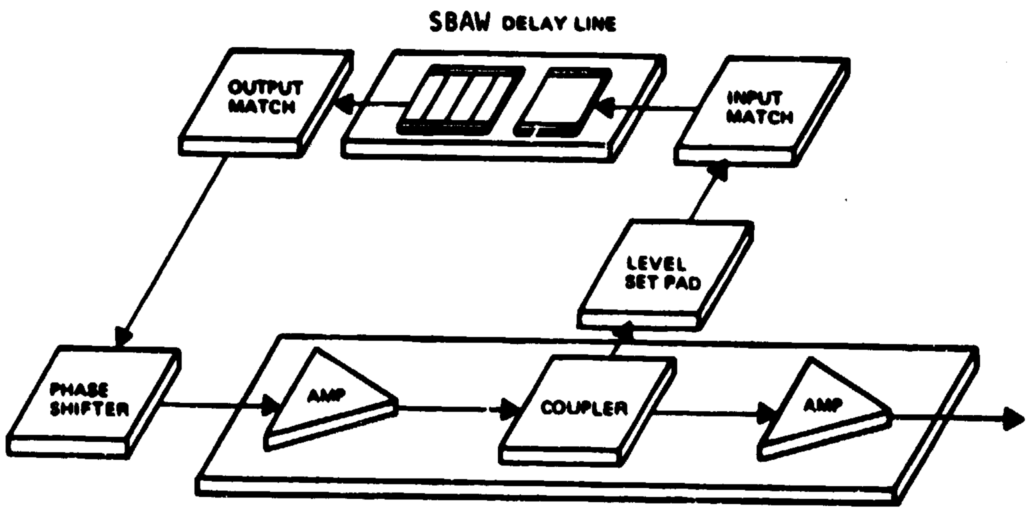

Figure 3-1. SBAW Oscillator Functional Diagram

loop is an integer multiple of 2π, and the gain of the amplifier is equal to or greater than the net insertion loss of the feedback elements. The conditions for oscillation can be expressed as:

$$\frac{2\pi f \ell}{V} + \phi = 2n\pi \tag{3.1}$$

and

$$L_S(f) + L_1(f) = G(f, A) \tag{3.2}$$

where

f = oscillation frequency

ℓ = center to center transducer separation

V = surface wave velocity

ϕ = phase shift through all elements except SBAW delay line

n = an integer

$L_S(f)$ = insertion loss of SBAW delay line

$G(f, A)$ = amplifier gain as a function of f and output level, A

Solving (3.1) for f

$$f = \frac{V}{\ell}\left(n - \frac{\phi}{2\pi}\right) \tag{3.3}$$

As a general rule, $L_1(f)$ and $G(f, A)$ are very slowly varying functions of f over a broad range around the frequency for which the oscillator is being designed, but $L_S(f)$ is a very strong function of frequency. The SBAW delay is designed as a bandpass filter whose response is ideally given by

$$L_S(f) = K \left(\frac{\sin X}{X}\right)^2 \left(\frac{\sin Y}{Y}\right)^2 \tag{3.4}$$

where

$$X = \frac{2\pi N(f-f_o)}{f_o}$$

$$Y = \frac{2\pi M(f-f_o)}{f_o}$$

K = insertion loss at f_o

N = number of finger pairs in first transducer

M = number of finger pairs in second transducer

$$K\left[\frac{\sin\left(\frac{2\pi N(f-f_o)}{f_o}\right)}{\frac{2\pi N(f-f_o)}{f_o}}\right]^2 \left[\frac{\sin\left(\frac{2\pi M(f-f_o)}{f_o}\right)}{\frac{2\pi M(f-f_o)}{f_o}}\right]^2 = G(f_o, A) - L_1(f_o) \tag{3.5}$$

It is clear that the ideal case would be obtained when (3.3) is satisfied at f_0. Equation (3.3) has nearly n solutions, but the gain term of (3.5) can be adjusted such that the only simultaneous solutions to both (3.3) and (3.5) occur in the immediate vicinity of f_0. So long as only one solution to (3.3) falls within the primary response of the SBAW delay line, single mode operation of the SBAW oscillator is guaranteed.

It is also evident from (3.3) that some frequency modulation of the SBAW oscillator is possible. Taking the derivative

$$\frac{df}{f} = \frac{-V d\phi}{2\pi \ell \phi} \tag{3.6}$$

This gives the expected result that the smaller the center to center transducer separation, i.e., the lower the delay line Q, the greater the SBAW oscillator tuning range. The usual method of accomplishing the tuning or frequency modulation is via a varactor diode phase shift network.

The output phase noise density of the SBAW oscillator can be expressed by

$$\text{Noise Power Density} = KT + NF + L + 20 \log \left[\sqrt{1 + \left(\frac{\omega_0}{2Q\Delta\omega}\right)^2}\right] \text{dBm/Hz} \tag{3.7}$$

where

KT = -174 dBm/Hz

ω_0 = the oscillator frequency

$L = L_1(\omega) + L_S(\omega)$

Q = the delay line loaded $Q(f_0/\Delta f_{3\ dB})$

$\Delta\omega$ = the offset frequency

Even when the bias conditions of the amplifier are carefully controlled, thermal noise and transistor noise will still result in oscillator phase and amplitude fluctuations. However, the phase noise component will generally dominate the amplitude noise. The noise power exhibits a floor at large offset frequencies which is determined by the amplifier noise figure and the delay line insertion loss. Minimum phase noise is achieved for minimum delay line loss, minimum amplifier noise figure, maximum filter Q, and maximum output power.

The preceding has established the design goals for the oscillator circuit, in particular equations (3.3), (3.5), and (3.7). The following discussion relates to the actual implementation of the circuitry surrounding the SBAW delay line.

3.2 HYBRID PACKAGED SBAW OSCILLATOR DESIGN CONCEPT

The 1.072 GHz hybrid packaged SBAW oscillator is functionally similar to previous TRW designs. The SBAW oscillator's circuitry was divided into two functional sections which were packaged separately. One hybrid package contains the SBAW delay line. The second contains the 1 GHz amplifier circuitry. A phase set coaxial line and level set attentuator which are used to control the oscillator's feedback characteristics are mounted external to the hybrid packages. The two hybrid packages with a minimum of external circuitry form a complete 1.072 GHz SBAW oscillator.

The SBAW oscillator circuitry was configured as two hybrids for several reasons. The primary consideration in selecting a two package design is that special handling and cleaning procedures are required by the SBAW delay line. This configuration places the active transistor amplifier circuitry and the SBAW delay line in separate hybrid packages which can be assembled using techniques and processes which are optimum for the specific devices involved. As a test circuit many SBAW delay lines can be evaluated using a small number of amplifier circuits.

The two-package design significantly reduces the possibility of damage to the SBAW delay line during the hybrid circuit alignment procedure. The amplifier circuit may require several iterative tuning operations during the same package. The two-package concept also has the advantage that the amplifier hybrid which is a wideband design can be used with different SBAW delay lines to build oscillators anywhere within the 800 to 1200 MHz design range. The external phase shifter and level set attenuator allows any amplifier and delay line hybrid to be used in an oscillator assembly. That is, they do not have to be built in a matched set.

3.3 1.072 GHz HYBRID PACKAGED SBAW OSCILLATOR DETAILED DESIGN

A schematic diagram of the 1.072 GHz hybrid packaged SBAW oscillator is shown in Figure 3-2.

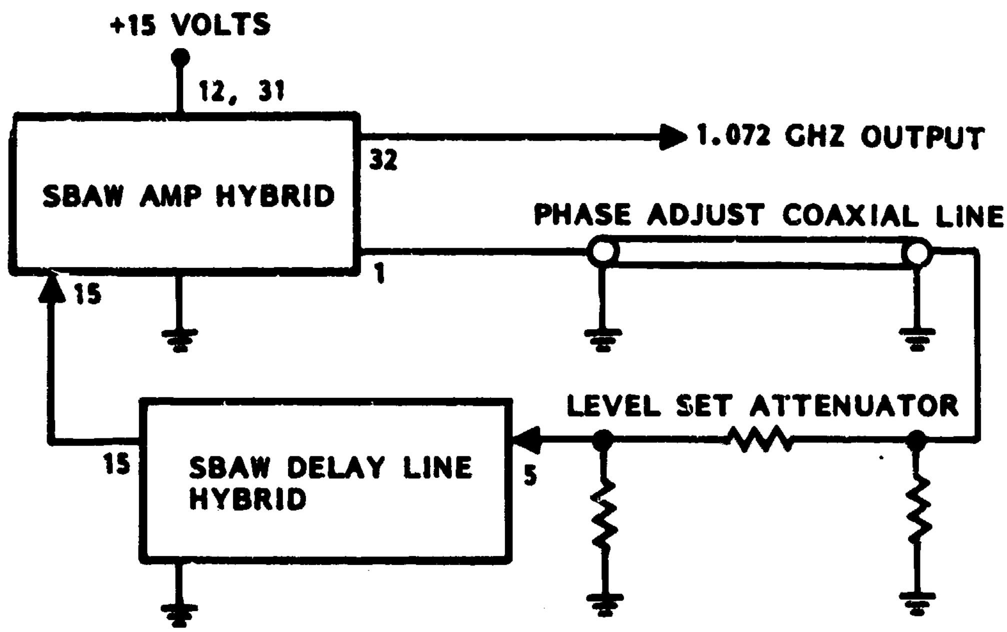

Figure 3-2. 1.072 GHz Hybrid Packaged SBAW Oscillator Schematic

The majority of the 1.072 GHz Hybrid packaged SBAW oscillator circuitry is contained within the SBAW delay line hybrid and the amplifier hybrid. The two hybrid packages and the external components used to set the feedback loop phase and amplitude are mounted on a duroid interconnect board.

The 1.072 GHz oscillator's feedback phase shift is set by selecting the proper length of a 0.020 inch semirigid coaxial transmission line to provide the necessary feedback loop phase shift. The feedback loop level set attentuator is also placed external to the hybrid packages on the duroid interconnect board. The attenuation is provided by a resistive pad consisting of a network of discrete chip resistors. These are the only two circuit functions that are not contained within the two SBAW oscillator hybrid packages. The complete 1.072 GHz SBAW oscillator assembly is mounted on a 3.4 x 2.7 x 0.25 inch brass plate.

The 1 GHz SBAW amplifier hybrid contains four amplifier stages and two Wilkenson power dividers. Four of the amplifier stages are part of the SBAW oscillator's feedback path and provide approximately 43 dB of loop gain. The amplifiers have been configured using two-stage designs consisting of two cascaded Hewlett-Packard HXTR 5001 transistors on each substrate. A block diagram of the 1 GHz SBAW amplifier is shown in Figure 3-3.

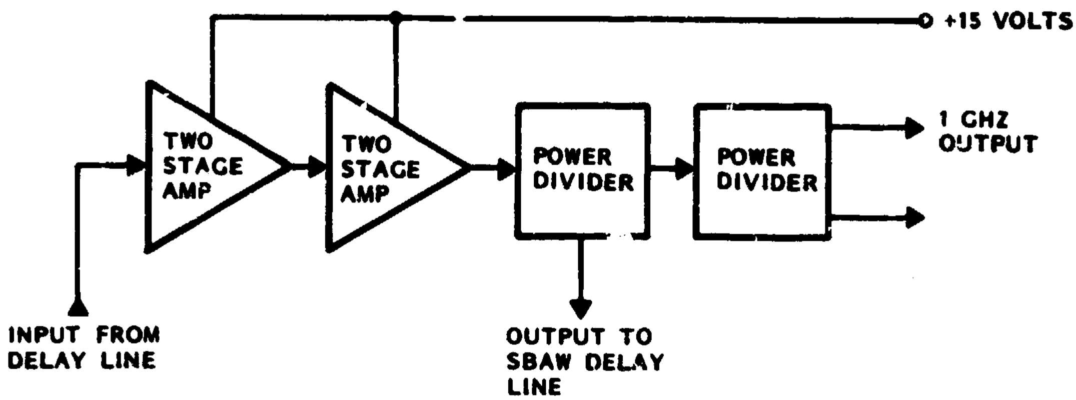

Figure 3-3. 1 GHz SBAW Amplifier Block Diagram

The amplifier was designed using CAD (computer-aided design) procedures and uses conventional RF circuit techniques. Each transistor uses gain compensating feedback in addition to broadband input and output matching circuits to achieve the desired bandpass characteristics. Then each is biased using an active bias network consisting of two 2N2907 transistors and an LM113 precision voltage reference. Two of the two-stage amplifier substrates are cascaded to provide the 46 dB of feedback loop gain. The output of the four-stage amplifier is power split by a Wilkenson 3 dB power divider. One side of the power divider provides the signal for the SBAW oscillator's feedback loop. The other power divider output drives the input of a second Wilkenson power divider. The output power divider provides two 1 GHz output ports.

The SBAW delay line is housed in an 0.625 x 0.625 x 0.009 inch hybrid package, TEKFORM 50116. Figure 3-4 is a photo of a SBAW oscillator.

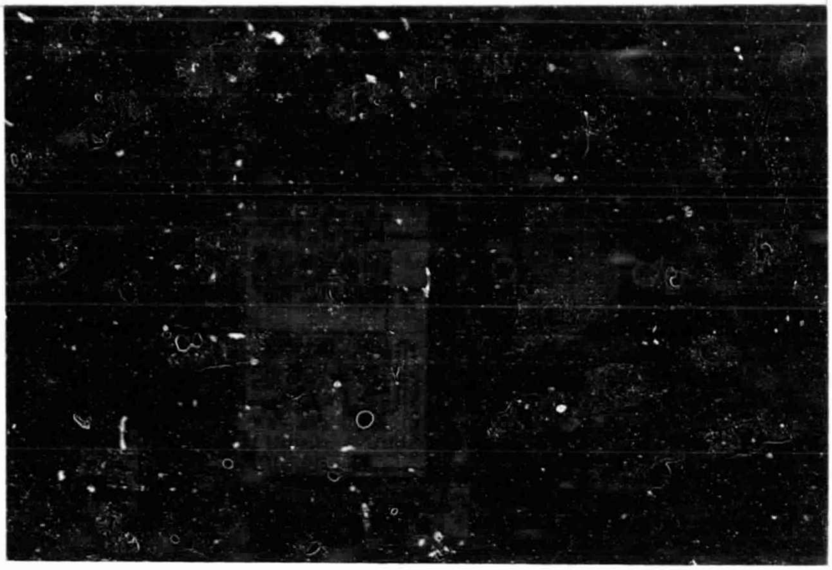

Figure 3-4. SBAW OSCILLATOR PHOTOGRAPH

3.4 1.072 GHz HYBRID PACKAGED SBAW OSCILLATOR DATA SUMMARY

The key performance parameters of the four 1.072 GHz SBAW hybrid packaged oscillators is summarized in Table 3-1. The temperature stability of the four 1.072 GHz SBAW oscillators varied from ±0.0025 to ±0.0047% over a -20 to +50°C temperature range. Figures 3-5 through 3-8 are plots of the temperature characteristics of the four SBAW oscillators.

Table 3-1. 1.072 GHz Hybrid Packaged SBAW Oscillator Data Summary

Parameter	SN35290-3	SN35288-3	SN352962	SN35289
Power Output	+6.6 dBm	+5.5 dBm	+5.5 dBm	+6.1 dBm
Frequency	1.07145 GHz	1.07172 GHz	1.07206 GHz	1.07166 GHz
Frequency Settability	± 0.83 MHz	± 1.065 MHz	± 1.035 MHz	± 0.8 MHz
Temperature Stability -20 to 50°C	± 0.0033 %	± 0.0025 %	± 0.0047 %	± 0.0042 %
Phase Noise dBc/Hz				
1 kHz	-86	-84	-84	-84
10 kHz	-106	-105	-105	-105
100 kHz	-126	-126	-125	-125
1 MHz	-145	-144	-142	-140

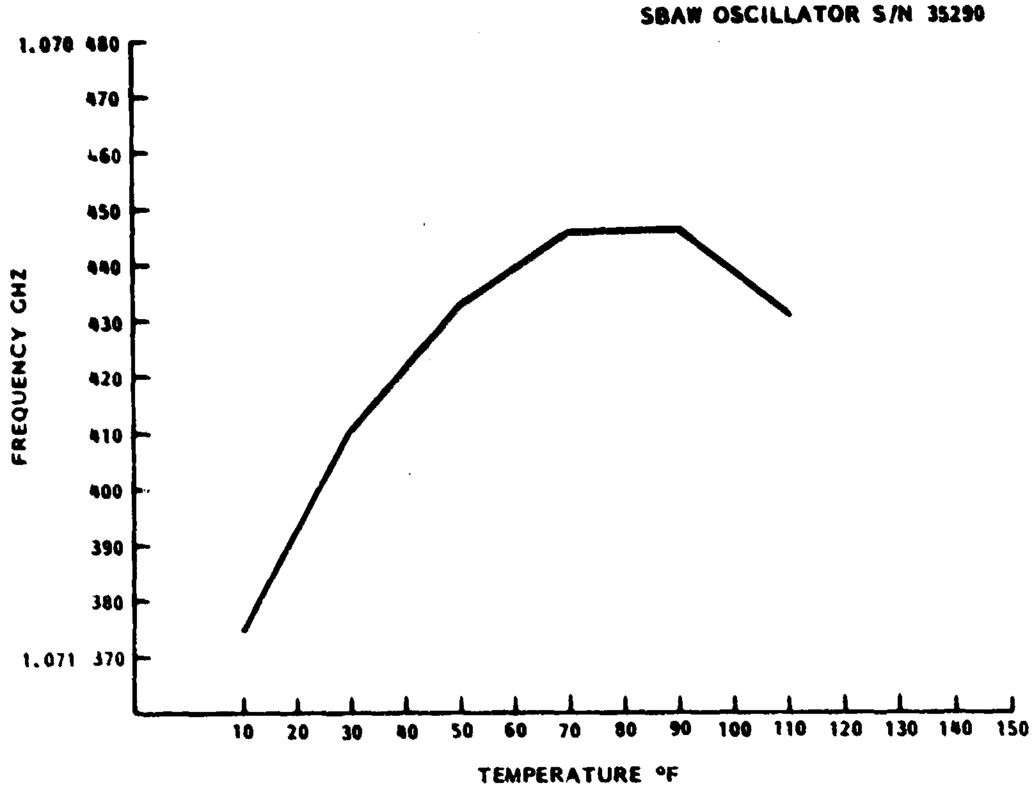

Figure 3-5. SBAW Oscillator SN 35290

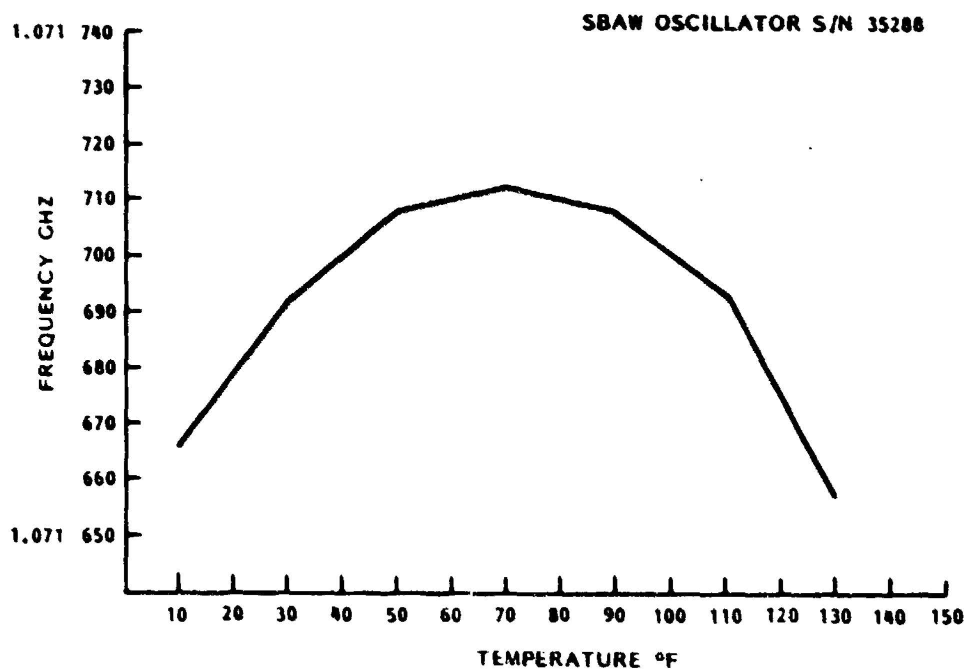

Figure 3-6. SBAW Oscillator SN 35288

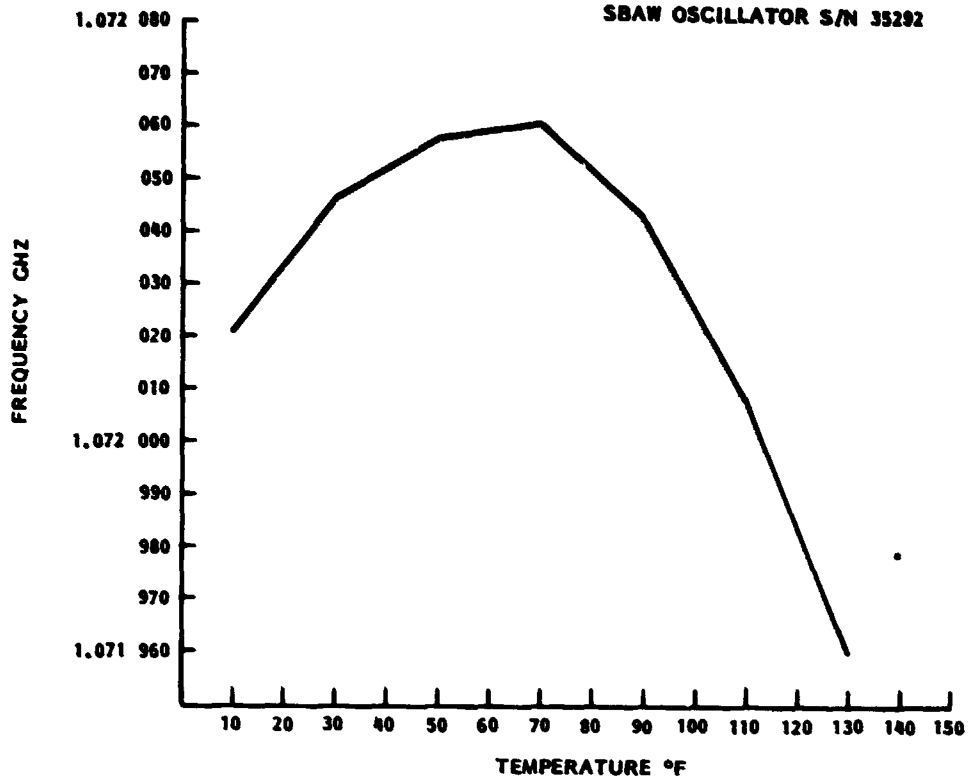

Figure 3-7. SBAW Oscillator SN 35292

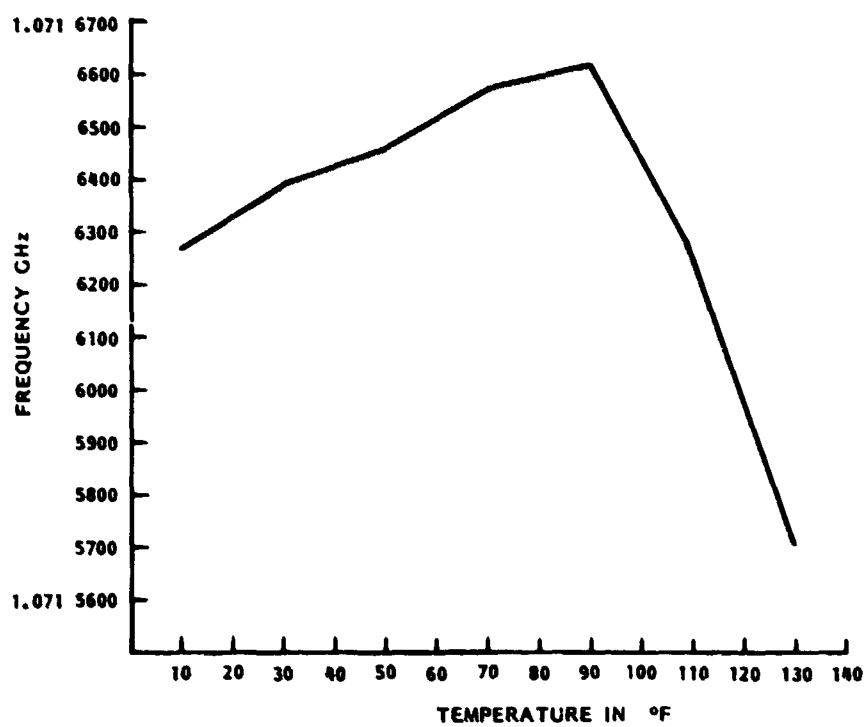

Figure 3-8. SBAW Oscillator SN 35289

The phase noise of the 1.072 GHz hybrid packaged SBAW oscillators was measured by TRW's metrology department; the measurements were made over a frequency range from 20 Hz to 1 MHz from the carrier. Phase noise plots of the four hybrid packaged 1.072 GHz SBAW oscillators are shown in Figures 3-9 through 3-12. The bandwidth of the phase noise measurement is a function of the offset frequency. At small offset frequencies, the measurement bandwidth is small and it increases as the offset frequency increases. A computer is employed to automatically adjust the bandwidth to optimize the sensitivity and the measurement time. The oscillator phase noise exhibits a 20 dB per decade slope, and the measurement setup has a noise floor approximately 15 dB below the measured data.

3.5 1.072 GHz SBAW OSCILLATOR AGING

Three of the four 1.072 GHz SBAW oscillators have been on an aging test since 3/3/81. The fourth unit was added on 5/6/81. The SBAW oscillators were temperature cycled between 10° and 150°F to mechanically stabilize them before the aging test was started. The temperature cycling minimized the frequency hysteresis caused by temperature induced mechanical stress and movement in the oscillator components. The oscillators were mounted on a common baseplate which minimizes temperature differentials between units. The frequency, output power and temperature of the SBAW oscillators was measured on a daily basis. Plots of the frequency characteristics of the oscillator are shown in figure 3-13 through 3-16. The oscillators have aging rates that vary from 0.020 ppm/day for SN 35288 to 0.062 ppm/day for SN 35292. Table 3-2 summarizes the aging rates for the four SBAW oscillators tested on this program.

Table 3-2. SBAW Aging Rate Summary

UNIT SN	AGING RATE ppm/day
35288	0.02
35290	0.062
35292	0.029
35289	0.021

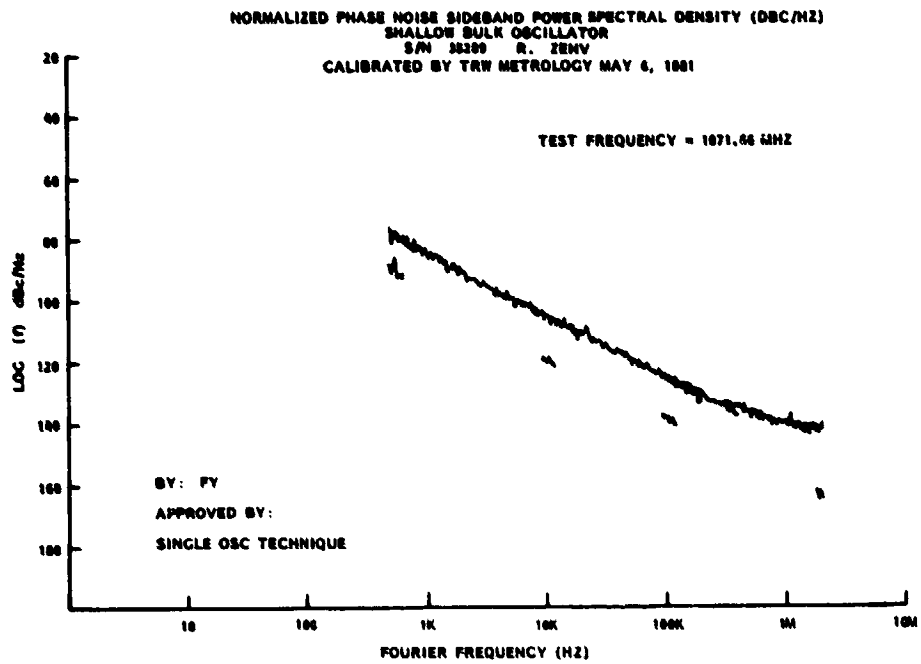

Figure 3-9. Normalized Phase Noise Sideband Power Spectral Density (dBc/Hz)
SN 35289

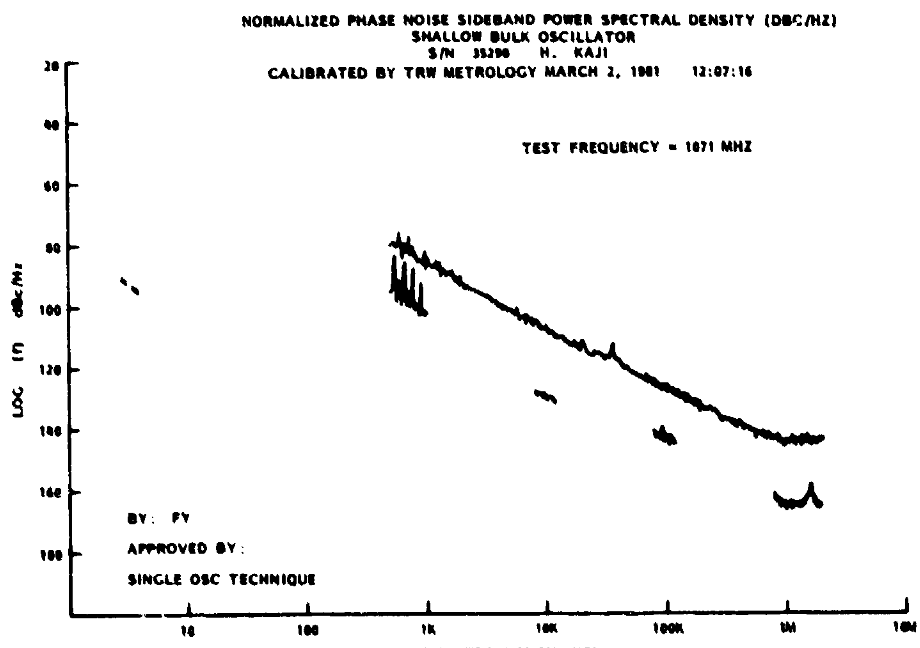

Figure 3-10. Normalized Phase Noise Sideband Power Spectral Density (dBc/Hz)
SN 35290

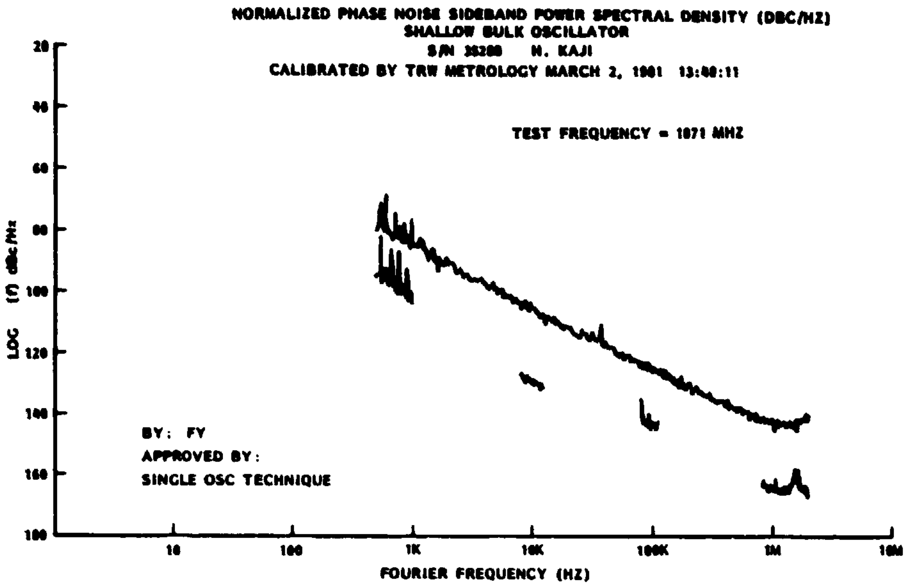

Figure 3-11. Normalized Phase Noise Sideband Power Spectral Density (dBc/Hz) SN 35288

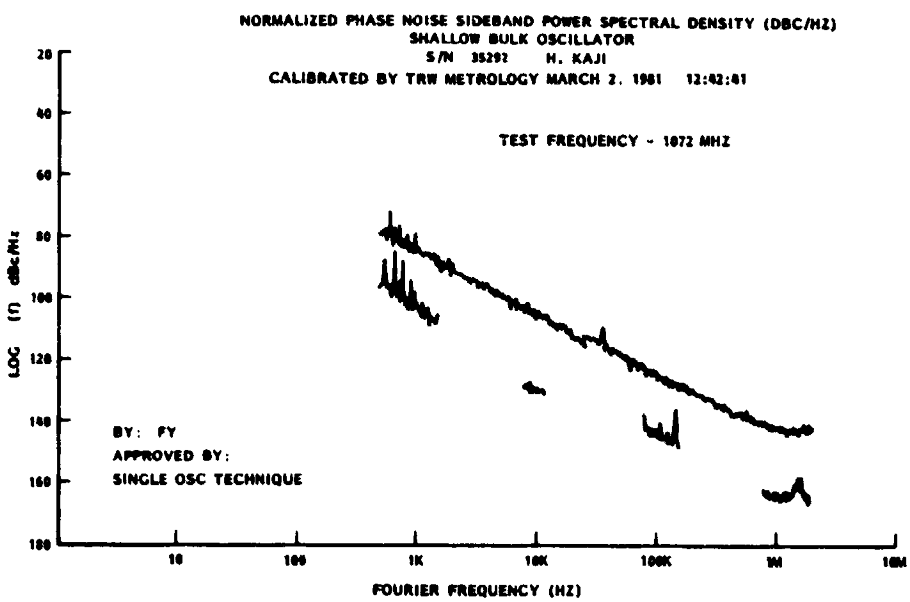

Figure 3-12. Normalized Phase Noise Sideband Power Spectral Density (dBc/Hz) SN 35292

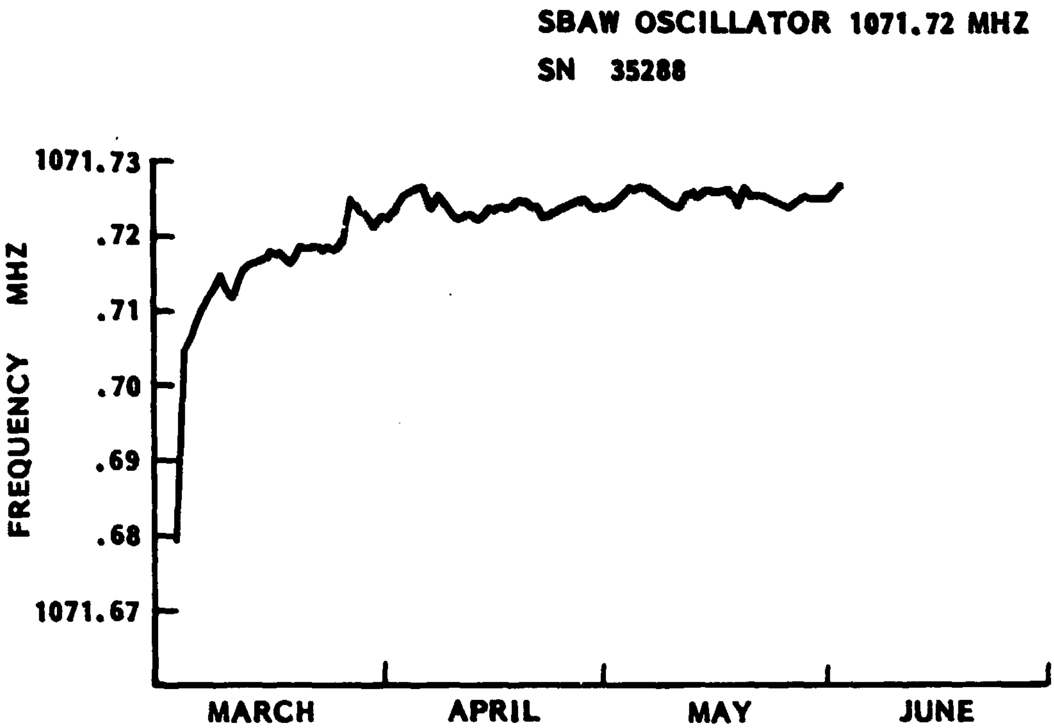

Figure 3-13. Aging Data, SN 35288

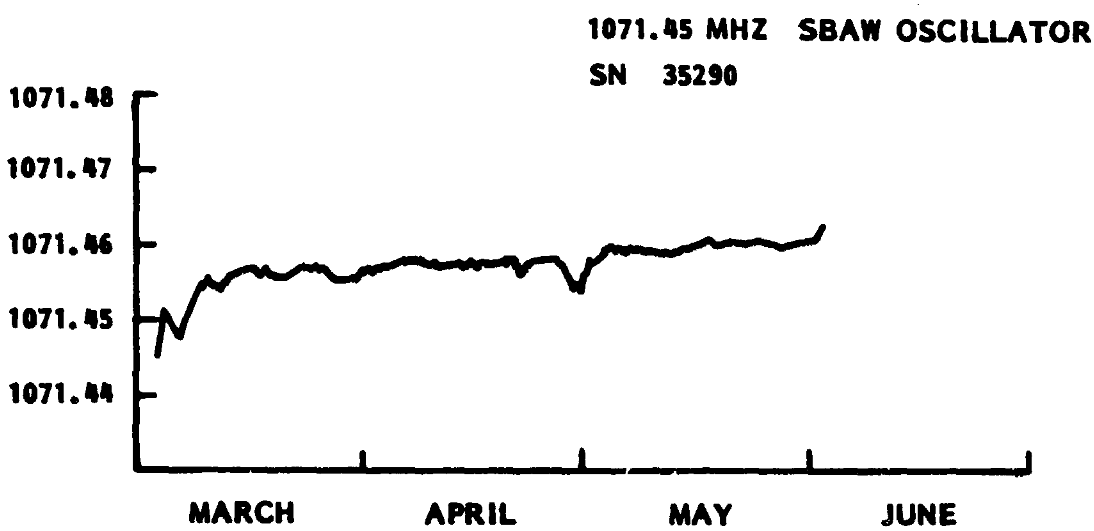

Figure 3-14. Aging Data, SN 35290

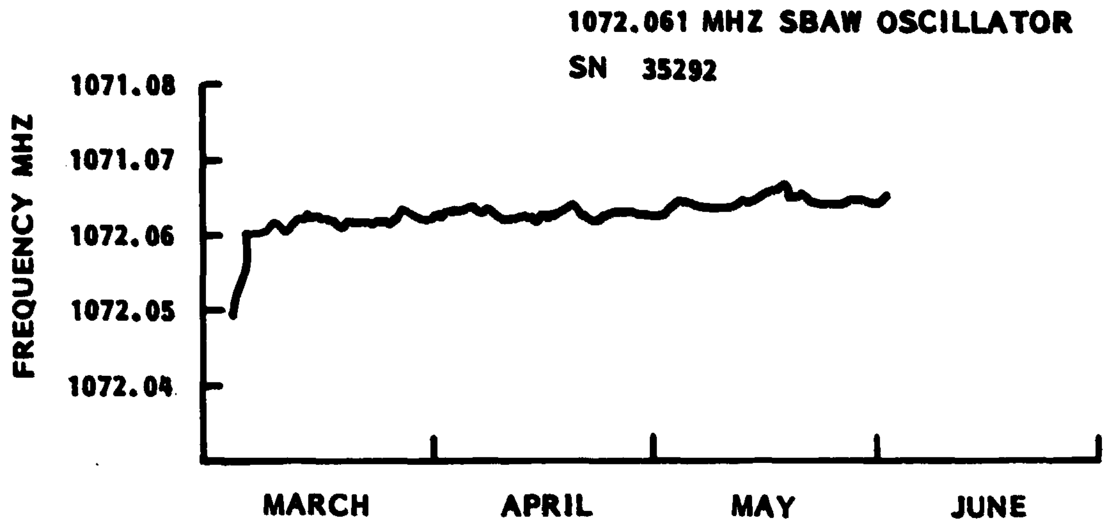

Figure 3-15. Aging Data, SN 35292

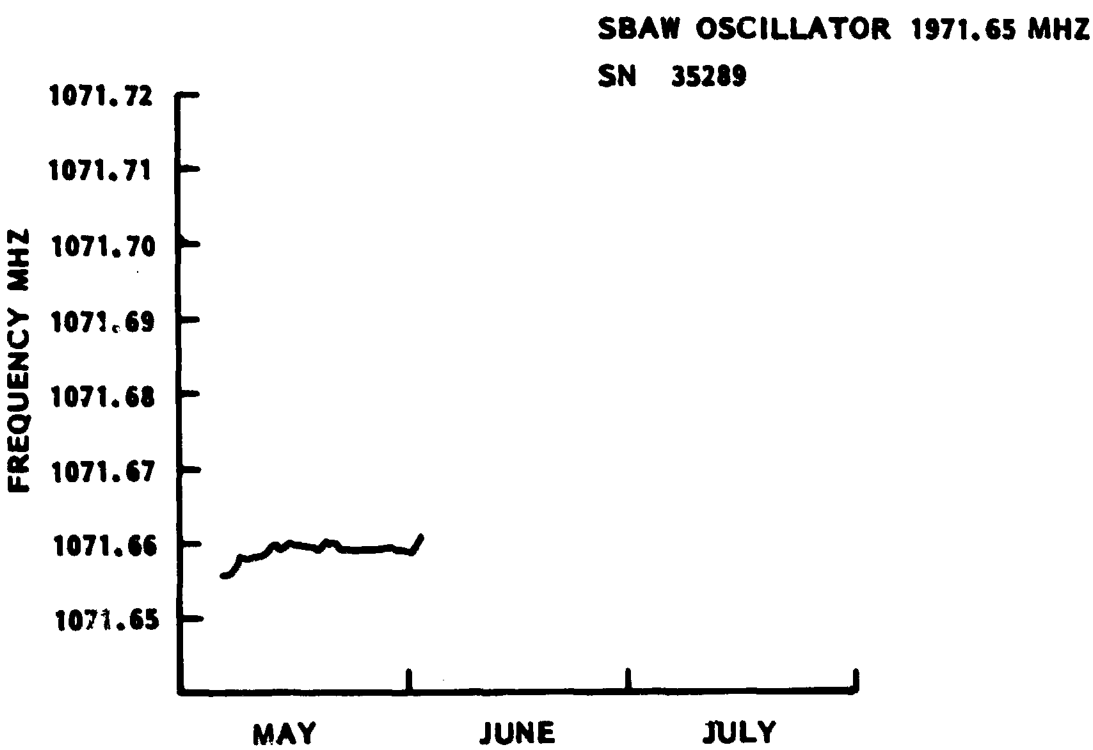

Figure 3-15. Aging Data, SN 35289

4. INVESTIGATION OF SBAW IN $A\ell N/A\ell_2O_3$

Aluminum nitride on sapphire ($A\ell N/A\ell_2O_3$) supports Surface Acoustic Waves (SAWs) which propagate at velocities close to 6170 m/sec. SBAWs, if found in this substrate, could potentially propagate at even higher velocities. These high velocities would allow one to construct devices well into the 3 GHz range and would greatly reduce the difficulty in fabricating 2 GHz devices.

Theoretical examination of the bulk mode structure was performed for the $A\ell N/A\ell_2O_3$ substrate. This approach examined $A\ell_2O_3$ and $A\ell N$ separately, then combined them to deduce the acoustic wave property of the composite structure.

For this investigation, the criterion for a SBAW substrate is that it support pure horizontal shear waves propagating along the surface. $A\ell N$ grows well on both R- and basal plane sapphire. As a result, both R- and basal plane sapphire were investigated.

The crystal symmetry of $A\ell_2O_3$ is $\bar{3}m$. Based on crystal symmetry and bulk mode considerations, bulk waves propagating along the surface of R-plane $(0\ 1\bar{1}2)$ sapphire are in general not pure modes.* A pure horizontal shear bulk mode exists in basal plane sapphire. The wave propagation direction is in the crystalline Y axis and the partical motion is parallel to the X axis. The wave velocity was calculated to be 6468 m/sec.

Coupling of the electric field to this horizontal shear mode in $A\ell_2O_3$ can be accomplished only with the presence of the piezoelectric $A\ell N$ film. The crystal symmetry of $A\ell N$ is 6 mm, and its piezoelectric coupling tensor can be written as

$$\begin{bmatrix} 0 & 0 & 0 & 0 & e_{x5} & 0 \\ 0 & 0 & 0 & e_{x5} & 0 & 0 \\ e_{z1} & e_{z2} & e_{z3} & 0 & 0 & 0 \end{bmatrix}$$

*B. A. Auld, "Acoustic Fields and Waves in Solids", Volume I, Chapter 7, J. Wiley & Sons, 1973.

To couple to the stress component (S_{xy}) of the horizontal shear wave, a non-vanishing element e_{x6} is required. It is clear that AℓN does not have the correct symmetry to couple the electric field of the interdigital transducer to the horizontal shear wave in basal plane $Aℓ_2O_3$. No useful SBAW of pure horizontal shear wave type can be found in the $AℓN/Aℓ_2O_3$ structure.

5. 2.144 GHz SBAW DELAY LINE STUDY

5.1 PROPOSED DESIGNS

The result of the 1.072 GHz SBAW Delay Line Study indicated that harmonic operating SBAW transducers are capable of high frequency operation while maintaining low insertion loss. This harmonic transducer concept was therefore extensively utilized in the 2.144 GHz SBAW Delay Line Study. The proposed design will include not only the third harmonic transducers, but also the fifth harmonic transducers. The fifth harmonic transducer configuration is shown in Figure 5-1.

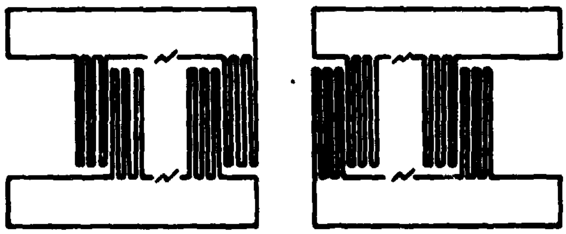

Figure 5-1. Fifth Harmonic Transducers

The 2.144 GHz delay line can be fabricated on either the 36.25° rotated Y-cut quartz or on the -50.5° rotated Y-cut quartz. The wave propagation direction is at 90° off the X-axis.

The proposed configuration as a result of this design study is summarized in Table 5-1.

Table 5-1. Comparison of the 2.144 GHz Delay Line on Different Rotations of Rotated Y-Cut Quartz

Substrate	36.25 Deg	-50.5 Deg
Harmonics	3rd	5th
Line Width	0.89 μm	0.65 μm
Transducer Length (Wavelength λ_0)	300 λ_0	300 λ_0
Metal Thickness/Groove Depth	300 Å/300 Å	300 Å/300 Å
Metallization	Aluminum	Aluminum

A comparison between the designs is summarized in Table 5-2.

Table 5-2. Comparison Between Two Designs

Substrate	36.26 Deg	-50.5 Deg
Mask Fabrication	Not Difficult	Difficult
Insertion Loss	< 28 dB Unmatched	35 dB Unmatched
Temperature Stability		
First Order Coefficient	0	0
Second Order Coefficient	$50 \times 10^{-9}/°C^2$	$16 \times 10^{-9}/°C^2$

5.2 PROPOSED FABRICATION PROCESS

The devices at 1 GHz were fabricated without using the embedded transducer configuration. At 2 GHz, the embedded transducer configuration must be employed to reduce propagation loss due to step discontinuities.

The fabrication process for the embedded transducer is shown schematically in Figure 5-2. After the photoresist pattern is developed, the substrate is ion-milled to create the desired groove depth. Aluminum metallization is then evaporated to fill up the grooves. The metal thickness must be within 100 Å that of the groove depth. This can be verified by surface profile measurement using a Dektak machine. A titanium layer of 30-40 Å can also be placed between the substrate and the aluminum to improve film adhesion.

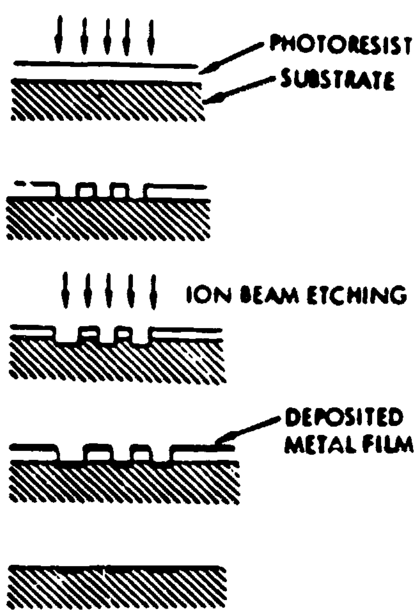

Figure 5-2. SBAW Delay Line Fabrication

6. FREQUENCY SELECTABILITY AND SETTABILITY

The output frequency of the SBAW delay line oscillator lies within the passband of the SBAW delay line. Within the passband, the frequency is set by the total phase shift around the oscillator loop. The coarse adjustment of the oscillator output frequency is therefore accomplished by adjusting the center frequency and bandwidth of the SBAW delay line. The fine tuning of the frequency is accomplished by mechanical or electrical phase shifters placed in the oscillator loop.

6.1 ADJUSTING THE FREQUENCY OF SBAW DELAY LINE

The fractional bandwidth of the SBAW delay line is a function of delay line design and is governed by the desired oscillator Q. The center frequency, on the other hand, depend not only on periodic space of the finger, but also on substrate orientation. As was shown in Figure 2-1, the wave velocity of SBAW in singly rotated Y-cut quartz is a function of substrate orientation. For a given mask design, the delay line output frequency can vary by as much as ± 21%, depending on the substrate orientation. For NASA application, the frequency slectivity requirement is from 2.1 to 2.3 GHz. This represents a fractional frequency range of only ± 4.5%. The method of adjusting the delay line frequency by adjusting the substrate orientation is therefore adequate for the NASA application. One mask design is thus sufficient to satisfy the frequency selectability requirement.

The method of frequency selectability by adjusting the substrate orientation was investigated both theoretically and experimentally. Theoretically, the wave velocity was found to change by more than 10% when θ varied from 35° to 55°. It was also calculated that the temperature coefficient and coupling coefficient also varied. Figure 6-1 showed the SBAW velocity and first order temperature coefficient of delay (TCD) as a function of substrate angle θ. This curve will be a useful reference for future design efforts.

SBAW delay lines were fabricated on 35.5°, 36.25°, 36.75° and 38° rotated Y-cut quartz. As shown in Table 6-1, good agreement between

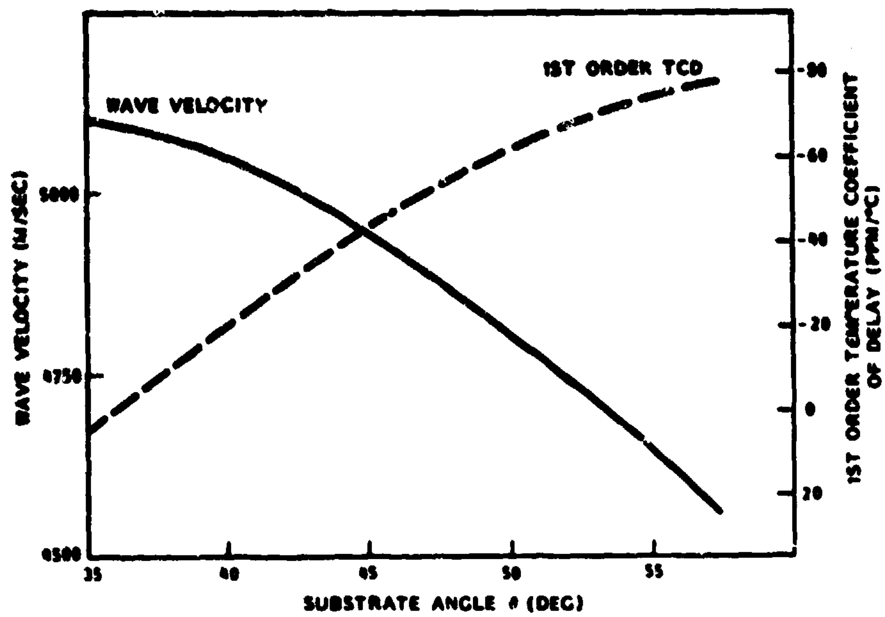

Figure 6-1. SBAW Velocity and First Order TCD as a Function of θ in Rotated Y-Cut Quartz.

Table 6-1. Comparison of Theoretical and Measured SBAW Velocity

Substrate Angle	Theory (m/sec)	Measurement (m/sec)
35.5	5093.2	5099 ± 2
36.25	5087.2	5094 ± 2
36.75	5082.5	5089 ± 2
38.0	5069.5	5067 ± 2

the theoretical and measured wave velocity was obtained. The effect of θ on the temperature coefficient of delay was also confirmed by experiment. The effect of changing θ is to shift the turnover temperature. This, in turn, resulted in a change of 1st order temperature coefficient of delay at room temperature (see Figures 6-2 and 6-3).

In addition to changing the substrate orientation, metal loading effect was also found to be a mechanism for adjusting the center frequency of the SBAW delay line. An experiment performed with a 2 GHz SBAW delay line was

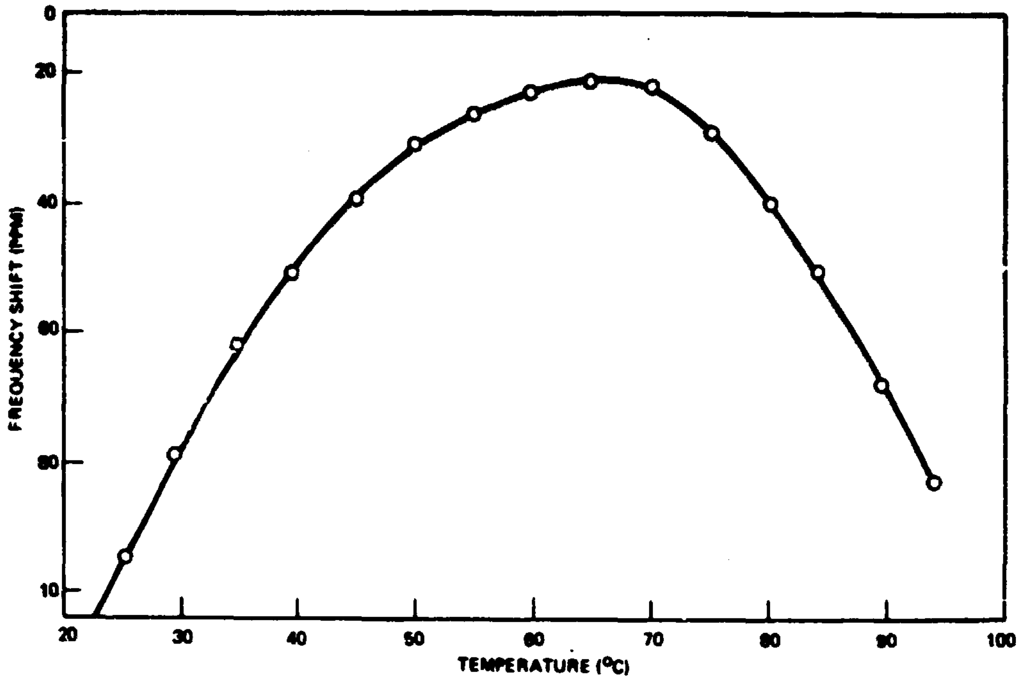

Figure 6-2. Temperature Stability of SBAW Delay Line. (With Energy Trapping Fabricated on 36.75° Rotated Y-Cut Quartz)

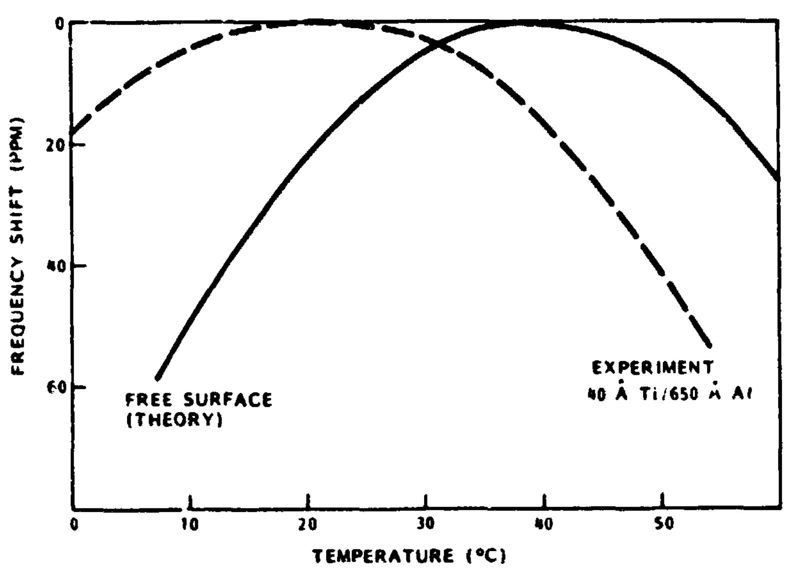

Figure 6-3. Temperature Stability of the SBAW Delay Line on 36.25° Rotated Y-Cut Quartz

reported in Figure 6-4. The center frequency was observed to shift by as much as 6% by adjusting the metal thickness in the SBAW transducer. This method of adjusting frequency also influences temperature stability. This is indicated by Figure 6-3 where the experimental turnover temperature is lower than the theoretical free surface value. The useful frequency settability range of this technique is actually less than 6%. This is because for thick metals, the insertion loss of the device becomes quite large. Useful frequency settability is approximately 2%.

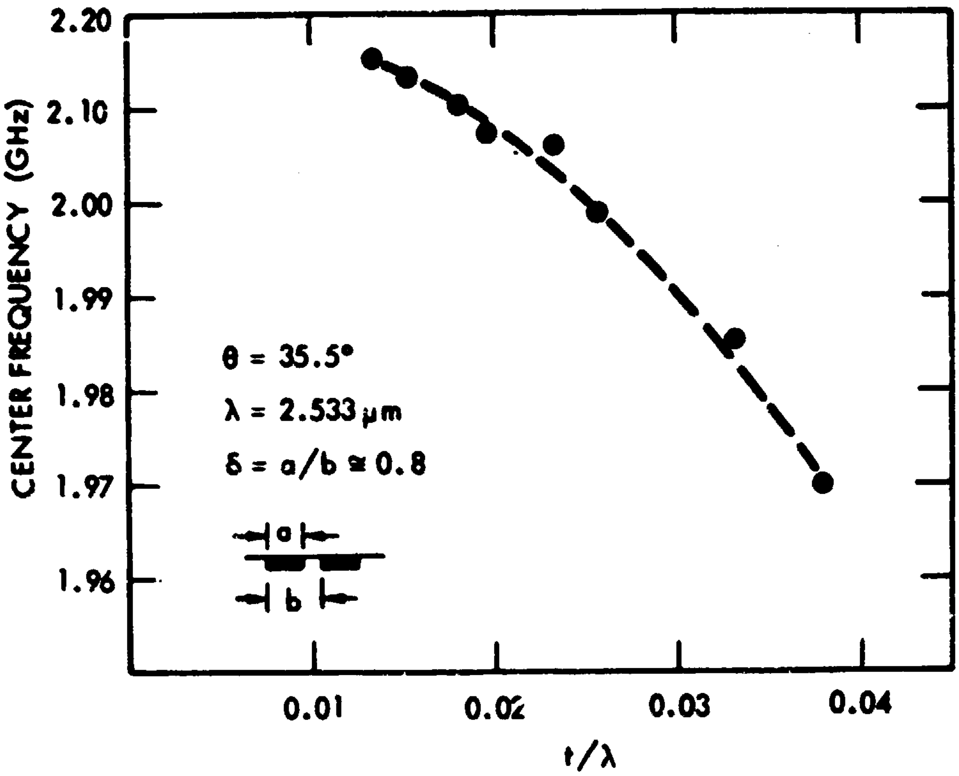

Figure 6-4. Dependence of Center Frequency as a Function of Normalized Metal Film Thickness.

6.2 FREQUENCY SELECTION THROUGH PHASE SHIFT ADJUSTMENT

The output frequency of the oscillator can also be selected within the passband of the SBAW delay line through adjusting the phase of the amplifier loop. For fixed frequency application, a coaxial line with specified length is adequate. For applications requiring tunability, electronic phase shifter may be used. To minimize temperature instability introduced by the electronic phase shifter, a combination of mechanical phase shifter and electronic phase shifter could also be proposed. In any case, the frequency settability of a SBAW oscillator depends on the phase settability. If one assumes that the phase settability of a phase shifter is approximately 1°, the frequency settability of an oscillator using a 2 MHz bandwidth SBAW delay line is approxiamtely 10 KHz.